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Road temperature variations
Hoar frost
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A description of a local climatological model used to predict temperature variations along stretches of road

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Summary

This paper includes a discussion of the factors causing large variations in temperature along stretches of road. These factors can be integrated into a local climatological model, and it is also shown how a model of this kind can be used to predict temperature variations along roads.

1. Introduction

Surveys of winter road conditions are traditionally based on information from field stations located in areas where large variations in temperature are found, as well as where road slipperiness frequently occurs. The most common methods for detecting such areas involve the use of instruments attached to cars, as reported by, for example, Lindqvist (1976), Thornes (1985), Smith (1988). Other methods involve the use of infrared equipment mounted on, for example, helicopters, as discussed by Stove *et al.* (1987) and Gustavsson and Bogren (1991). Several studies have demonstrated that a temperature survey of stretches of road using road weather sensors is very useful for the local road authorities (Lindqvist and Mattsson 1979, Lindqvist 1982, Thornes 1989). However, as discussed in several studies, e.g. Bogren (1990) and Gustavsson (1990a), recordings from field stations give only very localized information about road temperatures. There is therefore a need to extrapolate temperatures from the field stations to make them valid for larger areas. Such an extrapolation is not possible without taking the local topography into account. Variations in temperature can be dealt with, however, by constructing a model of the local environment along specific stretches of road.

The central focus of other studies dealing with the modelling of local climate has been to develop models in order to predict the variation in, for example, frost sensitivity, as discussed by Laughlin and Kalma (1988, 1990). The present paper describes how a local climatological model can be used to calculate air and road surface temperatures in an area with road weather sensors.

The paper consists of two parts. The first section deals with analyses of temperature recordings from field stations and from thermal mappings along stretches of road in order to determine the relationship between topography, weather and temperature variations. The second part starting with section 5 includes a discussion of the principles behind the modelling of local climate, as well as the procedure for adapting a model to a specific area.

2. Data

In order to study temperature variations along stretches of road, different types of recordings have been used. The data are obtained from:

(a) thermal mapping of road sections by use of instruments attached to a specially designed car, and

(b) field stations in the Swedish Road Weather Information System (RWIS) sited in different climatological environments along road sections.

2.1 Thermal mapping

The location of the sensor sites in the Swedish RWIS is determined after analysing thermal-mapping records obtained from cars. Thermal mapping produces continuous recordings along road sections. Air temperature is measured at 2 m and 0.3 m above the surface, humidity at 2 m and surface temperature by use of a thermal radiometer, all of which are recorded every 5 metres. The temperature recordings are stored in a computer, into which the driver feeds other parameters of interest to the analysis, such as information on road cuts, bridges, fog and changes in road surface construction.

In this study the thermal recordings have been used for analyses of the relationship between topography, weather and temperature variations. Using topographical maps (scale 1:50 000) in combination with field observations makes it possible to distinguish several types of topographical areas and their temperature differences compared with a reference temperature obtained from nearby neutral areas.

2.2 Field stations

The field stations are located at road sites which frequently suffer from slipperiness. Typical locations are, for example, valleys, bridges and road cuts. At all stations the air temperature and humidity are measured at the height of 2 m and the road surface temperature by use of a probe in the top layer of the road coating. Some of the stations have extra equipment, such as sensors for wind speed, wind direction, precipitation and for detecting dry or wet road surfaces.

As the field stations are located in different types of area, these recordings allow a good overall evaluation of temperature variations between different types of location. The method used for the analyses comprises a comparison between neutral and exposed location. From the integration of weather parameters obtained from nearby synoptic weather stations and wind recordings from field stations, the variation caused by these parameters can be determined.

3. Repetition of temperature patterns

The fundamental idea behind modelling local climates for prediction of temperature variations is that the temperature pattern is repeated during situations with similar weather. Huovila (1964) and Mattsson and Börjesson (1978) have shown that there is a high correlation between different measuring trips carried out along the same route during clear, calm nights.

Air temperature recordings from three measuring trips along road 60 between Falun and Borlänge in the county of Kopparberg, Sweden, are shown in Fig. 1. The recordings were carried out on 19, 22 and 23 January 1986, all three at approximately 2200 LST. During the three nights the sky was cloudless. A light wind of approximately 1 m s^{-1} was blowing on 19 January, but the other two nights were calm. The correlation between the lowest air temperatures is very high, as can be seen in the figures, and the temperature patterns along the road during the three nights are very similar. The lowest air temperature was to be found in three distinct valleys along the road, as well as in an open arable area at a distance of 13 km from the start. However, during 19 January when light winds were blowing, this area did not have such a low temperature as on the two other measuring trips. This can be explained by the fact that the open area is very exposed to the wind, a factor obstructing stabilization of cold air during windy nights.

The three measuring trips presented in Fig. 1 show the same result as the measurements presented by Huovila (1964) and Mattsson and Börjesson (1978) discussed above. This theorem forms the basis for modelling local climate. It is possible to make a highly accurate prediction of the temperature variation in an area, especially when discussing forecasting of temperature variations along a road section which is thermally mapped. This reasoning is also valid for weather situations which are not clear and calm, as the temperature pattern is to a high degree controlled by local topography and other factors which it is possible to determine. This is discussed further in the following sections, in which each factor is treated separately.

4. Analyses of geographical factors controlling temperature variations

4.1 Valleys

Accumulation of cold air in valleys during clear, calm nights results in a varying air temperature pattern along road stretches. In a study by Bogren and Gustavsson (1991) it was demonstrated that the variation in temperature between valley bottoms and summits can be related to such factors as the valley geometry, i.e. the width and depth of the valley. Another important factor was found to be the wind exposure of the valleys. The return period of the occurrence of the cold air pool, as well as the magnitude of the temperature difference, increased if the valley location was in any way sheltered from the wind by, for example, trees.

Gathering of cold air in valleys causes a reduction of the road surface temperature (RST) compared to the RST of nearby neutral areas. As shown in Gustavsson (1990b) and Bogren and Gustavsson (1991), the lowering of the road surface temperature is linearly related to the lowering of the air temperature, i.e. the

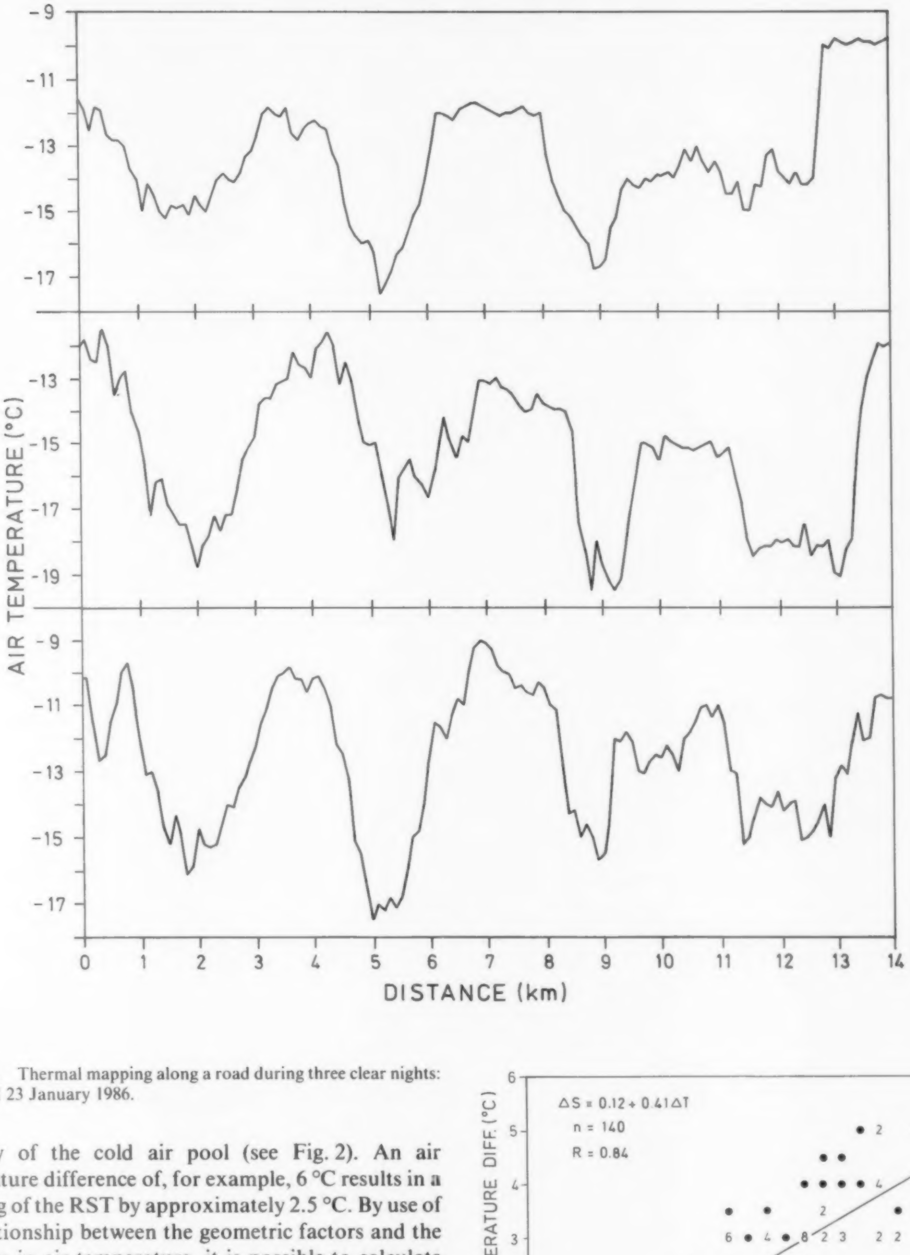


Figure 1. Thermal mapping along a road during three clear nights: 19, 22 and 23 January 1986.

intensity of the cold air pool (see Fig. 2). An air temperature difference of, for example, 6 °C results in a lowering of the RST by approximately 2.5 °C. By use of the relationship between the geometric factors and the variation in air temperature, it is possible to calculate the variation in road surface temperature.

4.2 Variation in altitude

Under cloudy, windy conditions variations in temperature are largely due to changes in altitude, and the influence of local topography is most reduced. By the action of wind and counter radiation from clouds the temperature differences are generally small.

In order to calculate the temperature variations during this type of weather, the heights above sea level at

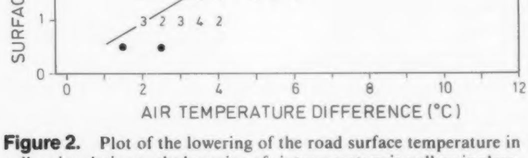


Figure 2. Plot of the lowering of the road surface temperature in valleys in relation to the lowering of air temperature in valleys in clear, calm weather (Bogren and Gustavsson 1991).

which the stations are sited are used together with air and road surface temperatures as inputs to a regression model. From the regression equations, the distribution of air and road surface temperature as a function of altitude is determined. Under fully mixed conditions, the temperature falls by approximately 1 °C per 100 m. This tendency is a general one and can be used for both night and day.

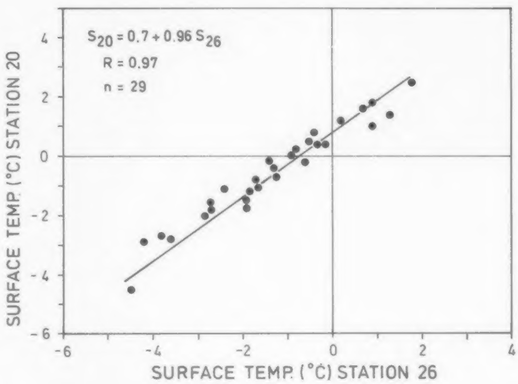
The effect of cloudy, windy conditions on the temperature lapse rate is illustrated in Figs 3(a) and 3(b). The two RWIS stations which are used in this example cover an altitudinal range of 150 m. Station 20 is situated at 170 m, while station 26 is sited at 320 m. The relation between the minimum road surface temperatures (RST) of the two stations is expressed by the equation $RST_{20} = 0.7 + 0.96\ RST_{26}$, with a correlation coefficient of $r = 0.97$. The number of observations was 29. This implies a decrease in road surface temperature of 0.64 °C per 100 m change in altitude. The minimum air temperature (AT) behaves in the similar way as the road surface temperature. The regression for the air temperature is $AT_{20} = 0.98 + AT_{26}$ with $r = 0.96$, i.e. a change in temperature of 0.67 °C per 100 m.

4.3 Screening

On clear days the screening effect must be considered when analysing temperature variations along road sections. Especially during the spring and autumn, screened areas can be prone to localized risk of slipperiness. A study by Bogren (1991) demonstrates that the factors of greatest importance when considering screening effects are the position of the sun in relation to the site (time of day and season) and the type of object, together with its orientation in relation to the orientation of the road. The intensity of the temperature difference which develops between the screened and exposed sites is also affected by the amount of cloud. That the orientation and geometrical configuration of the screening object are the most important factors controlling the variation in surface temperature during sunny days has also been documented in a study by Gustavsson and Bogren (1991).

The effect of screening objects on the road surface temperature is illustrated by a thermal recording from a measuring trip by car on a clear day, Fig. 4. The measuring trip was conducted on highway No. 40 between Gothenburg and Landvetter, in the western part of Sweden. This is a good example of a road section where screened and open areas alternate. The screening objects are mainly in the form of road rock cuts. Since the orientation of the road is primarily east–west, parts of it are screened during the middle of the day and afford a good opportunity for study.

The measuring trip was carried out in the early afternoon on 6 March 1990. The weather preceding the measuring trip was clear and calm; these conditions also prevailed during the thermal recording. The areas which were not screened from the sun had a relatively high



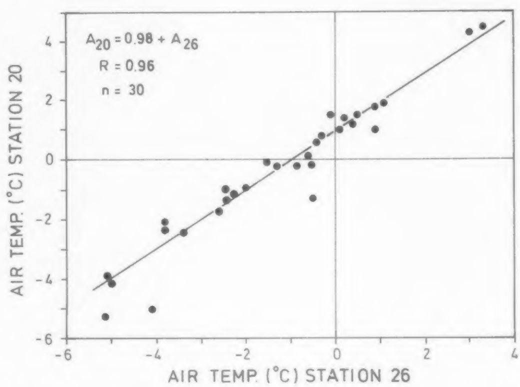


Figure 3. Plots of (a) minimum road surface temperature, and (b) minimum air temperature for cloudy, windy nights from two field stations whose altitudes differ by 150 m.

surface temperature, approximately 11 °C. The difference in temperature between the screened and exposed parts of the road section varied between 5.7 and 2.3 °C. The variation among the 13 screened areas can be explained by two of the major factors, the exact orientation of the road rock cut and its height.

By use of information about the position of the sun together with data on the screening objects, it is possible to calculate the temperature difference between screened and sun-exposed areas. An additional input is gained from the road surface temperature values recorded at the RWIS stations along the road sections in question.

5. Modelling of local climatological areas

The following section describes the principles of the local climatological model used to predict temperature variations along stretches of road. The different units described in the previous section form the basis for calculations of temperature variations. Since different weather conditions require that different factors are taken into account, the model is subdivided into five sections each dealing with a specific weather condition. This subdivision is further described below together with the background information needed for an

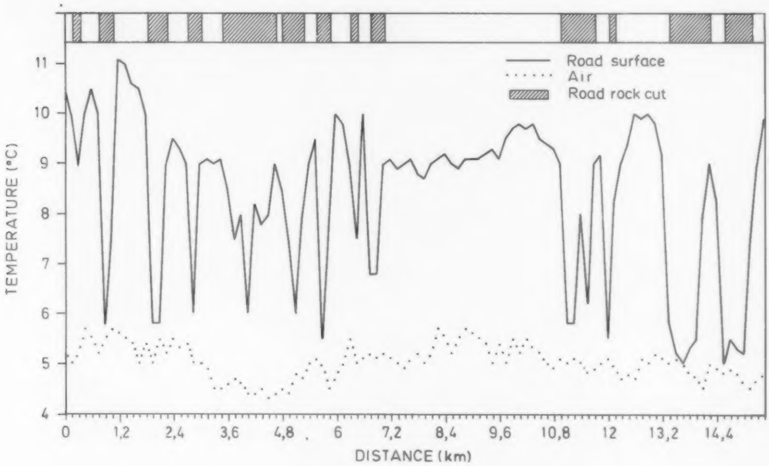


Figure 4. Thermal mapping along a road during a clear sunny day, 6 March 1990.

adaptation of the model to a specific area. An example of the procedure behind the adaptation of the model to the county of Halland, south-west Sweden, is presented in Gustavsson and Bogren (1990).

The data required for adapting the model to a specific area include thermal mappings along the road sections, and historical data from the field stations in the area. Both types of recordings are necessary, as they serve as a basis for the model adjustment in two different ways. The thermal recordings give information about the location and extent of variations in air and road surface temperatures, as well as the relative differences in the temperature between specific areas, while historical recordings are used to confirm the temperature variations determined from the thermal mappings. These recordings are also used to study the temperature differences which occur and to link them up with the prevailing weather conditions.

The road sections included in the model are classified and subdivided into segments with the help of topographical maps on a scale of 1:50 000 and field measurements and checks of the topographical properties (see Fig. 5, for example). The field checks are very important, especially for determining the exact orientation of road stretches and the type and density of objects causing shadow patterns. The extent and position of each type of variation which must be dealt with in the model are derived from analyses of the temperature recordings and maps.

The local climatological model uses four different types of temperature patterns depending on the prevailing weather situation. These types are:

day/clear
night/clear
cloudy, windy
regional pattern.

A subdivision of these types of pattern is made according to the amount of wind and cloud which is indirectly measured by the temperature variations at the field stations in the area discussed.

The algorithm which is used for the calculation of the temperature pattern along the stretches of road has different criteria for the decision as to which temperature pattern is currently valid. The criteria are successively considered until the temperature information can be applied on the different segments along stretches of road.

The first level in the algorithm includes a determination of actual time, and in the daytime the system starts to compare the theoretical calculations for screening effect with the values that are recorded from the RWIS system. If the required criteria are not fulfilled the algorithm continues to investigate if there is a temperature decrease with increasing height — if not, the model chooses the regional temperature distribution.

At night the criteria for pooling of cold air and its effect on the road surface temperature are tested. If the required criteria regarding wind speed and temperature differences match the actually recorded values the model uses the night/clear temperature pattern. If the wind speed is high and the temperature pattern smooth, the algorithm tests the correlation between absolute height and temperature fall. In situations with a high correlation between increasing height and falling temperature, the model output results in the temperature pattern decreasing temperature with increasing height. The regional temperature pattern is used if the criteria for decreasing temperature with increasing height are rejected.

If an external temperature forecast is added as an input to the model it is possible to use the algorithm for prediction of temperature values.

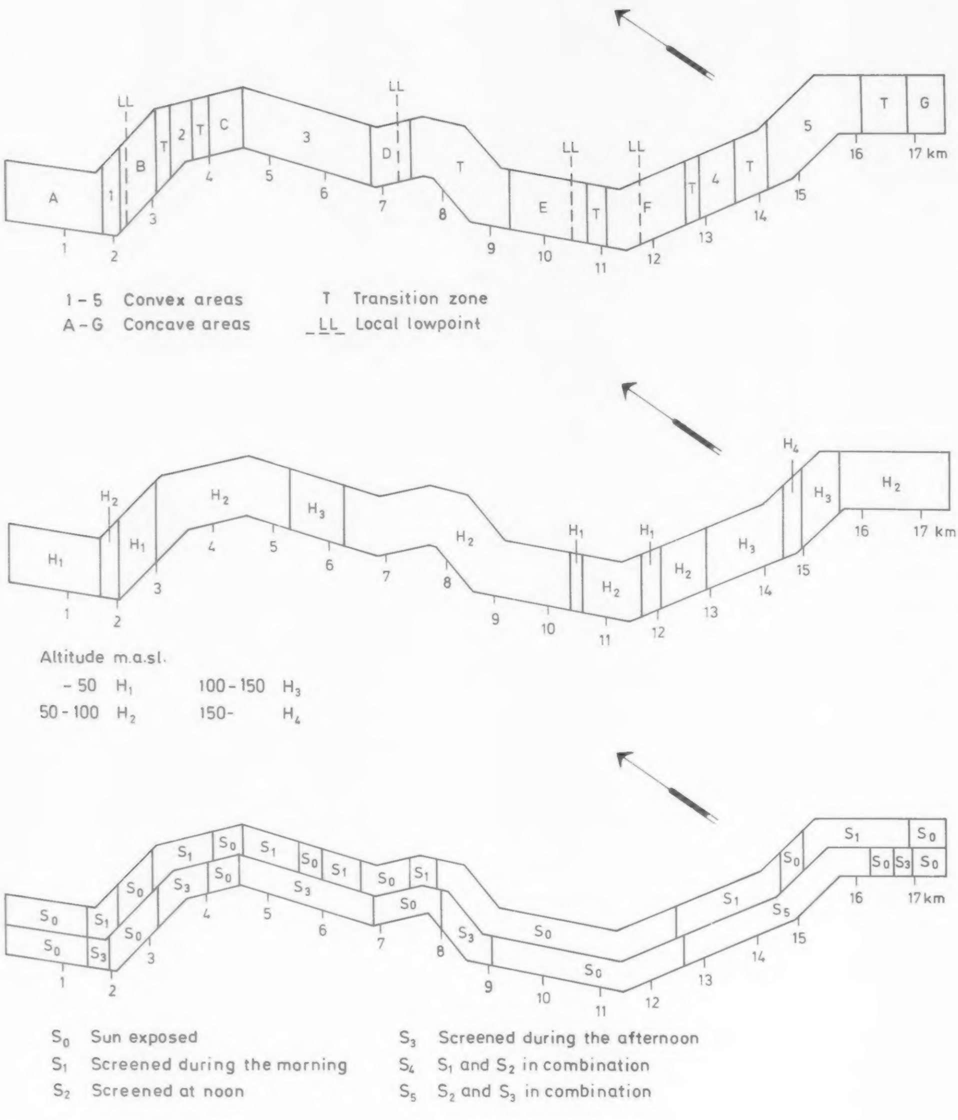


Figure 5. Subdivision of a road into segments used in the local climatological model for (a) calm nights, (b) cloudy, windy situations, and (c) clear days.

To be able to model the temperature patterns along a stretch of road under varying weather conditions, the stretch must be divided into significant topographical segments. Fig. 5 shows three different segments for road No. 156, western Sweden. The topographical units used to determine the temperature pattern in situations with potential for development of cold air pools are convex areas, concave areas, transition zones and local low-points.

On a clear calm night, the pooling of cold air is concentrated in the concave areas where the local low-points form the lowest temperatures. The concave areas are often open and relatively well exposed, which makes them favourable to accumulation of cold air but also sensitive to disturbance by the wind. Convex areas are neutral areas which are relatively elevated and thus do not permit pooling of cold air. The transition zones are located in the stretch between the convex and concave areas and they can be affected by cold air in extreme situations. Calculated air temperature differences between the concave and convex areas in relation to the geometric properties of the valley are shown in Table I for a clear, calm night. The table also includes measured temperature differences for the same situation.

The variation between measured and calculated temperatures is generally small. The maximum error is 1.0 °C for area F (see Fig. 5(a)).

When the weather situation is characterized by cloudy, windy conditions the model takes advantage of the relation between the temperature lapse rate and altitude. In such situations, the temperature pattern is calculated using the topographical units which are based on the absolute height above sea level of a certain road section. For road section No. 156, Fig. 5(b), four different levels, H_1–H_4 are used. The segments cover an interval of 50 metres starting with H_1 for the 0–50 m interval. The temperature pattern may be calculated with the help of a regressions calculation where the values recorded at the RWIS stations in the area are used as input data. The result from a calculation referring to a cloudy, windy situation is given in Table II. On this occasion the temperature decreased by 0.8 °C per 100 m. The input temperature which is given from a reference station (H_0) along the road is −1.2 °C in this situation, this temperature thus yielding for the H_0 segment.

The temperature pattern under clear-day conditions is determined by topographical object which can give a shadow pattern. The segmentation for these occasions is done according to the time period during which there is a shadow pattern. Five differently screened classes are used, where S_0 represents a sun-exposed area, S_1 — screening during the morning, S_2 — screening at noon, S_3 — screening during the afternoon, S_4 — S_1 and S_2 in combination and S_5 — S_2 and S_3 in combination (Fig. 5(c)). The calculated RST variations along road No. 156 under clear-day conditions are shown in Table III. The road surface temperature is calculated as the difference between sun-exposed and screened sections for 15 January, 15 February and 15 March at 1000 and 1300, respectively. As a result of the variation in the maximum solar elevation during the period, the maximum temperature difference varies accordingly.

The examples given in Fig. 5 cover three of the weather situations included in the model. Variations of these weather conditions are also taken into account, i.e. the temperature pattern is calculated using subdivisions where various wind and cloud conditions are considered. Weather situations other than those discussed above are dealt with using, for example, the regional temperature distribution determined by the regional climate. A more detailed description of how this is performed is given in Gustavsson and Bogren 1990. Here, the influence on the road surface temperature of variations in traffic density and road construction material is dealt with in a more general way, and not in relation to specific weather situations.

6. Discussion

Ideas similar to those presented in this study concerning prediction of temperature variations along stretches of road have been used in the United Kingdom. However, a much more simplified technique was used as a base for the extrapolation of temperatures. From temperature recordings along a specific stretch of road, thermal maps are constructed for three types of atmospheric conditions: extremes (i.e. clear, calm nights), intermediate (some influence from clouds and

Table I. Air temperature difference between concave and convex segments in a clear-night situation, see also Fig. 5(a)

Segment	Valley width (km)	Valley depth (m)	Cold air pool intensity		
			Calculated (°C)	Measured (°C)	Calculated−measured (°C)
A	1.8	5	5.0	5.4	−0.4
B	1.0	20	4.0	3.5	0.5
C	0.5	5	2.0	2.0	0
D	0.6	35	4.0	4.0	0
E	1.6	0	3.0	3.5	−0.5
F	1.6	0	3.0	4.0	−1.0
G	0.6	20	3.0	3.0	0

Table II. Calculated road surface temperatures under cloudy, windy conditions, see also Fig. 5(b)

Segment	H_{abs} (m)	H_{rel} (m)	RST_{cal} (°C)	RST_{actual} (°C)
H_1	0–50	0	T_r	−1.2
H_2	50–100	50	T_r−0.4	−1.6
H_3	100–150	100	T_r−0.8	−2.0
H_4	150–200	150	T_r−1.2	−2.4

H_{abs} — Absolute height, interval 50 m.
H_{rel} — Height relative to H1.
RST_{cal} — Calculated road surface temperature relative to T_r, T_r is the road surface temperature at the reference station.
RST_{actual} — Actual road surface temperature.

Table III. Calculated road surface temperature differences under clear-day conditions on 15 January, 15 February and 15 March at latitude 57° N at 1000 and 1300, see also Fig. 5(c). These are the differences between sun-exposed and screened areas.

Segment	15 January RST_{diff} (°C)		15 February RST_{diff} (°C)		15 March RST_{diff} (°C)	
	10h	13h	10h	13h	10h	13h
S_0	0	0	0	0	0	0
S_1	−0.8	0	−2.5	0	−7.4	0
S_2	0	−2.2	0	−3.2	0	−4.3
S_3	0	0	0	0	0	0
S_4	−0.8	−4.1	−2.5	−7.6	−7.4	−15.8
S_5	0	−2.2	0	−3.2	0	−4.3

S_0 — Sun-exposed area
S_1 — Screening during the morning
S_2 — Screening at noon
S_3 — Screening during the afternoon
S_4 — S_1 and S_2 in combination
S_5 — S_2 and S_3 in combination

wind) and damped (fully mixed conditions). A weather forecast is used for the decision which type should be used.

The model presented in this paper uses, as previously described, several types of background data in order to develop the empirical relationships used for extrapolation of temperatures. Different segmentation is further used for different weather conditions as well as time of the day and the Julian date in the year. With the aid of all this information together with the real-time observations from the field stations a much more diversified temperature pattern can be obtained and the accuracy of the temperature forecast improved.

The benefits of using a local climatological model such as the one described in this paper are several compared with a road weather information system based only on field stations, the most important naturally being that the area covered by the information system is much larger, resulting in a more diversified snow and ice control. Computerized maps of the temperature variations along stretches of road can be used by the road authorities and by others to determine the local risk of slipperiness. The information from the model may be combined with a temperature forecast to obtain a prognosis of the temperature pattern for the coming 4–6 hours, as well as a prognosis of the risk of road slipperiness, not only at specific locations but for the whole area covered by the model. Another advantage is that the information received by the superintendent includes greater details, which results in a more restricted use of means of combating snow and ice, such as salt.

Acknowledgements

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Persistent hoar frost

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The frosty period of weather in southern England from 6 to 15 December 1991 provided opportunities for the photographic observations of persistent hoar frost and its growth in the author's garden (183 m above mean sea level).

Passage of a weak cold front from the east on Thursday, 5 December 1991 effectively cleared a persistent blanket of stratocumulus which had been causing 'anticyclonic gloom'. After six frosty nights, with negligible thawing by day in the shade, Fig. 1 shows the sharp, crystalline, vertical hoar frost growths some 1–2 cm high on short grass (at the edge of the path) and beech leaves over bare soil — the photograph being taken at 1430 UTC on the 11th. There is very little growth of crystal on the clay earth itself, suggesting that the capture of moisture from a saturated atmosphere by projections near the ground had occurred. Small movements of air in the light, variable winds within the sheltered garden probably account for the more randomly orientated profusion of crystals which had formed on the blade edges of longer grass.

Following three more frosty nights, some freezing fog causing rime deposition, and a little thawing by day, the hoar frost growths had become 2.5 cm high (Fig. 2, taken at 1430 UTC on the 14th). A maximum of 3 cm was measured early on the 15th before a very rapid thaw ensued during the morning.

Hewson and Gait (1992) do not appear to have mentioned if surface friction bears any relation to hoar frost 'deposition'. From the above photographic evidence (albeit taken in a sheltered situation) one suspects that a rough road surface (e.g. loose chippings) is more likely to capture low-level moisture from the atmosphere than a smooth one (e.g. tarmacadam).

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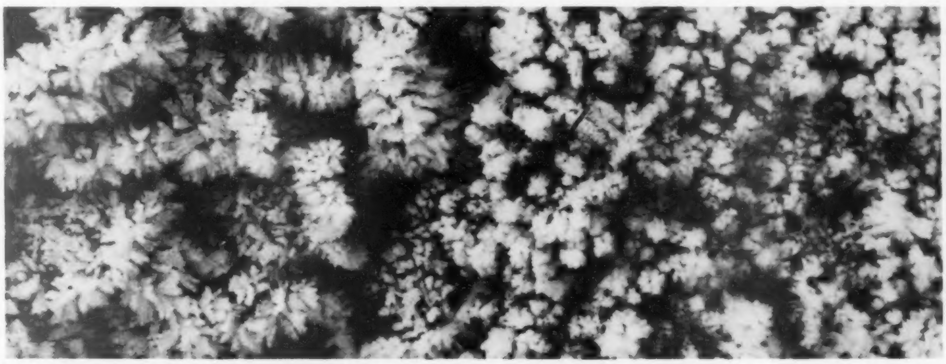

Figure 1. Hoar-frost deposition on short grass (right-hand side) and beech leaves and soil (left-hand side), see text for date and time.

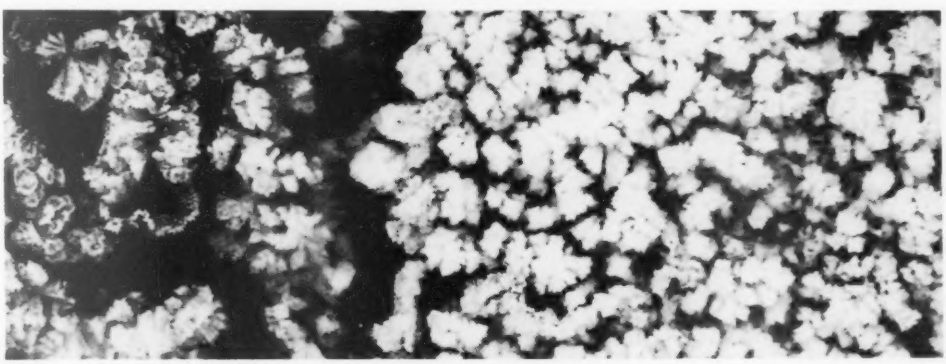

Figure 2. As Fig. 1 but three days later.

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Extreme rainfall at Hewenden Reservoir, 11 June 1956

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Summary

One of the most intense rainfalls within a 2-hour period in Great Britain was recorded during a severe thunderstorm on 11 June 1956 at Hewenden Reservoir. Later, doubts were raised about the validity of this observation, because the storm efficiency appeared to be too high. However, a re-examination of the meteorological situation on that date and investigation of the scale of the resulting flood seem to suggest that the original measurement may have been correct.

1. Introduction

The 11th of June 1956 was a day noted for the development of severe and widespread thunderstorms in Britain, with damage reported from places as far apart as the Isle of Wight, Wales and Inverness-shire. The outstanding storm, however, was in West Yorkshire between Bradford and Keighley where a rainfall of 155 mm in 105 minutes beginning at 1745 UTC was reported at Hewenden Reservoir. This was of particular interest because, at that time, it substantially exceeded the highest recorded rainfall in a comparable period (122 mm in 2 hours (1895)); and even today remains one of the highest rainfalls observed in a period of about 2 hours (Table I). But the observation was rejected as 'not acceptable' in the Flood Studies Report (FSR) (Natural Environmental Research Council 1975), based on studies of the storm efficiencies of six other major 2-hour storms and an estimated dew point of 12 °C on 11 June 1956. In fact the fall was down-rated to 102 mm on the implicit assumption that the original observation exceeded the local Probable Maximum Precipitation (PMP).

It is important to establish, as far as possible, the facts about this observation, particularly because, of the four highest falls in about 2 hours, only the Hampstead one is fully authenticated (Table I). In the case of Walshaw Dean Lodge the reading was not accepted by the Meteorological Office on the grounds that the gauge overflowed and the reading exceeded the PMP for the area. Also the radar observations were much lower; but recent analyses (Acreman and Collinge 1991) provide a possible explanation for this, and evidence provided by Acreman (1989) also supports the original rainfall observation. In the case of Camelford substantial amounts of hail fell during this storm. The officially accepted value is 139 mm (Meteorological Office 1957) but Bleasdale (1957) states that a minimum of 25 mm water equivalent of hail was not collected by the gauge.

Unfortunately no investigation of the Hewenden Reservoir storm was published at the time, though the Meteorological Office made some enquiries. However, the authors have made an extensive search for information, the results of which are described in this paper.

It seems that the representative dew-point for the Hewenden storm was underestimated, which has led to a considerable overestimation of the storm efficiency associated with the observed rainfall. It is believed that the validity of the original observation has been restored.

Table I. Maximum observed rainfall values for durations of 1½–2½ hours

Rainfall (mm)	Duration (min.)	Date	Place
193	120	19 May 1989	Walshaw Dean Lodge
171	150	14 Aug. 1975	Hampstead
161	150	8 June 1957	Camelford
155	105	11 June 1956	Hewenden Reservoir
137	135	10 Aug. 1957	Llansadwrn
136	150	4 Aug. 1938	Torquay
132*	120	6 June 1963	Southery
130	120	5 Sept. 1958	Knockholt
126	120	11 July 1932	Cranwell

* An unofficial gauge; reading reported by Jackson (1979)

2. Meteorological situation on 11/12 June 1956

On the 11th, Great Britain was under the influence of a weakening ridge joining two high pressure systems, one east of Scandinavia and one west of Spain (Fig. 1). Blocked by this ridge, a low had moved north to Iceland and its cold front moved slowly east as the ridge weakened. At the same time a depression over northern Germany moved slowly west towards the Netherlands. Associated weak north-easterly surface winds over Britain were bringing warm air from Scandinavia to Central England. The accompanying warm front was almost stationary on 11 June, but was replaced on the 12th by the cold front associated with the approaching Atlantic depression.

At 1200 UTC on the 11th, over the whole of Great Britain, light north-easterly surface winds of 5–15 knots brought in moist, warm air from Scandinavia. The air was particularly moist on the east coast of England with dry-bulb temperatures of 13–15 °C and dew-points of 9–14 °C (relative humidity ≈ 85%); whereas the air mass over the western British Isles was drier, with higher temperatures (15–21 °C) and dew-points (12–16 °C) (relative humidity ≈ 70%). The skies were only partly cloudy in the west, allowing the surface to be heated by direct sunlight and producing convectively unstable conditions. Most stations in the east recorded complete cloud cover.

During the afternoon convection developed and cumulonimbus clouds were widespread over Great Britain. Showers and thunderstorms were reported from the south of England up to Scotland.

3. Development of storms on 11 June

The general weather situation on 11 June 1956 in Great Britain provided all the necessary features for the development of severe convective storms.

3.1 Availability of moist air in the lowest levels.

The dew-point maps for 1200 UTC show rather high dew-points of 14–16 °C over central England. The warm, moist air mass expanded north during the day and at 1800 UTC a warm air tongue stretched from central England to southern Scotland, producing rather steep dew-point gradients in northern England (Fig. 2).

Hewenden Reservoir is located between Manchester, Lindholme and Dishforth, with the last two being upwind of the storm. The dew-point in Manchester fell during the afternoon, while at Lindholme and Dishforth the dew-points rose (see Table II). This suggests that the dew-point at Hewenden Reservoir probably lay between 15° and 16 °C at the time of the outbreak of the Hewenden storm on the evening of 11 June (Fig. 2).

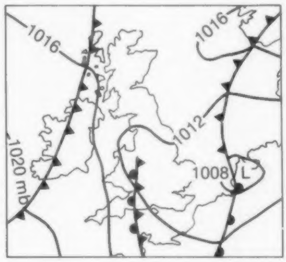

Figure 1. Surface chart for 1800 UTC on 11 June 1956.

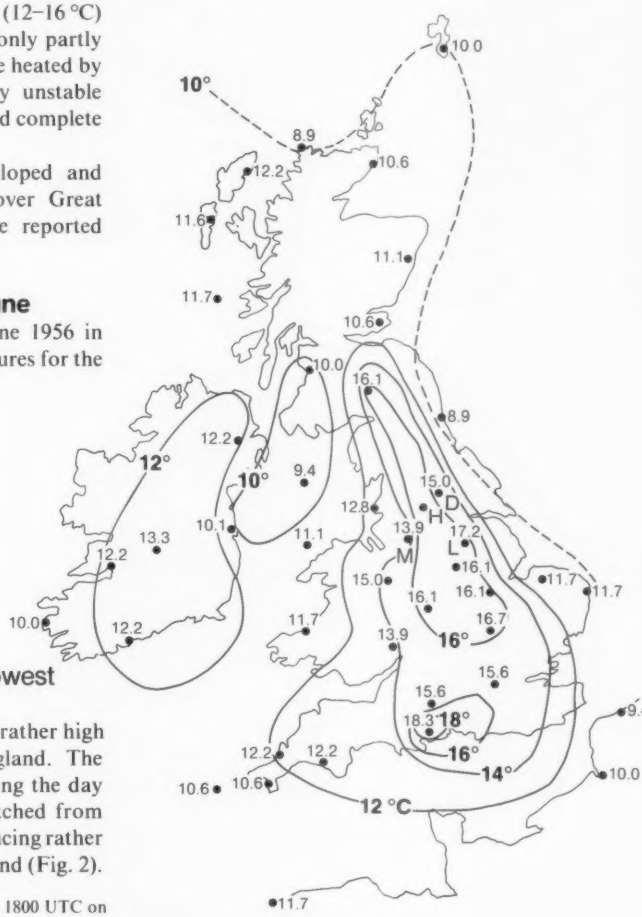

Figure 2. Readings and isotherms of dew-point for 1800 UTC on 11 June 1956. M, L, D and H label the positions of Manchester, Lindholme, Dishforth and Hewenden respectively.

3.2 Wind shear between lower and upper levels

The surface flow was light north-easterly, associated with the depression over the Netherlands. The flow in the middle troposphere was veering during the day from easterly to south-westerly, implying an increasing wind shear in the lower troposphere. This wind shear is important for the development and duration of severe storms, because it feeds the system with fresh, moist air from the lower levels and it also facilitates the venting of air descending from middle levels (Sumner 1990). It separates updraughts and downdraughts, so that they can co-exist and co-operate, rather than interfere destructively (Ludlam 1980).

3.3 Convective instability

The combination of wind field, warm, moist air masses over central and northern England, and the approaching cold front produced a high degree of convective instability over most parts of Great Britain, especially in the south and the central part of England. In the afternoon convection developed, giving rise to the formation of cumulonimbus clouds and thunderstorms, which were reported mainly in regions of high dew-points (Figs. 2 and 3).

The map showing the location of thunderstorms on 11 June 1956 (Fig. 3) proves that convective instability was widespread over Great Britain, though concentrated over central England. Thunderstorms were reported in Scotland (Inverness-shire) around 1300 UTC, in northern Cumbria around 1400 UTC, but most of the storms broke out between 1700 UTC and 1900 UTC in central and southern England.

4. The Hewenden storm

Details of the storm and the resulting damage have been obtained from several sources: articles in two local newspapers (the *Keighley News* and *The Yorkshire Observer*), photographs in the archives of those newspapers, a report by Mr J.S. Lattin (at that time Surveyor to Bingley Urban District Council), the Meteorological Office and Yorkshire Water plc.

The storm occurred between Bradford and Keighley, in an area where the land is rising from the river Aire in a generally west-south-westerly direction to the moors which form part of the Pennines (Fig. 4).

The newspapers reported a violent thunderstorm which struck the area bounded by the villages of Cullingworth, Oxenhope and Oakworth. A member of the British Thunderstorm Census, living in Oakworth, recorded 115 flashes of lightning. Information about the time of the storm comes mainly from the rainfall observations —at Hewenden Reservoir the rain lasted from 1745 to 1930 UTC, and at Stubden Reservoir from 1745 to 1900 UTC. According to the *Keighley News* the storm was 'at its height' between 1745 and 1830 UTC.

Table II. Dew-points for Manchester, Lindholme and Dishforth for the times shown 11/12 June 1956

Stations	11th 1200	11th 1800	12th 0000
	Dew-points (°C)		
Manchester	15.6	13.9	10.6
Lindholme	14.4	17.2	12.2
Dishforth	12.8	15.0	11.7

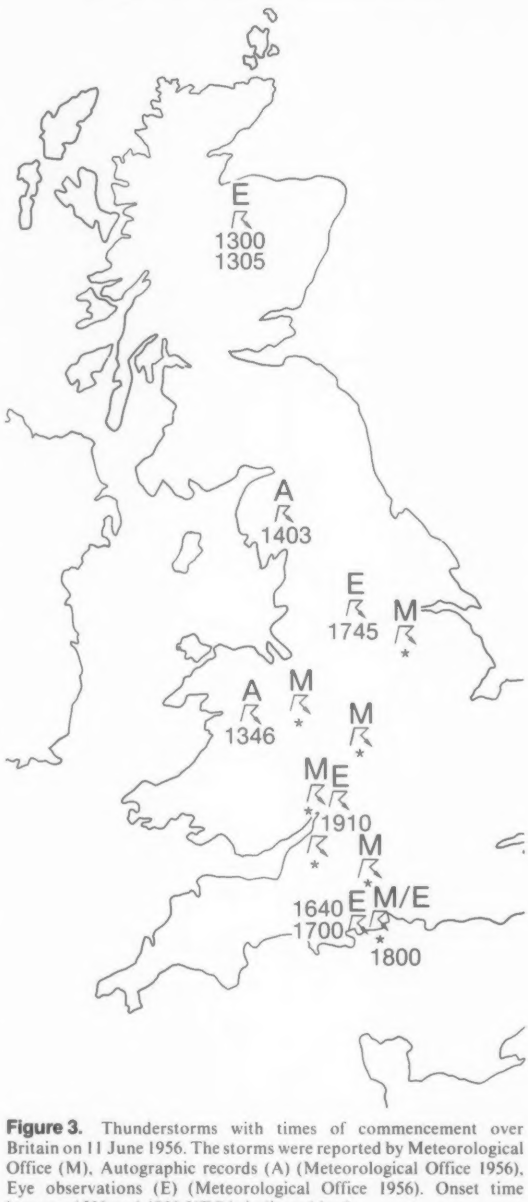

Figure 3. Thunderstorms with times of commencement over Britain on 11 June 1956. The storms were reported by Meteorological Office (M), Autographic records (A) (Meteorological Office 1956), Eye observations (E) (Meteorological Office 1956). Onset time between 1500 and 1800 UTC is indicated by *.

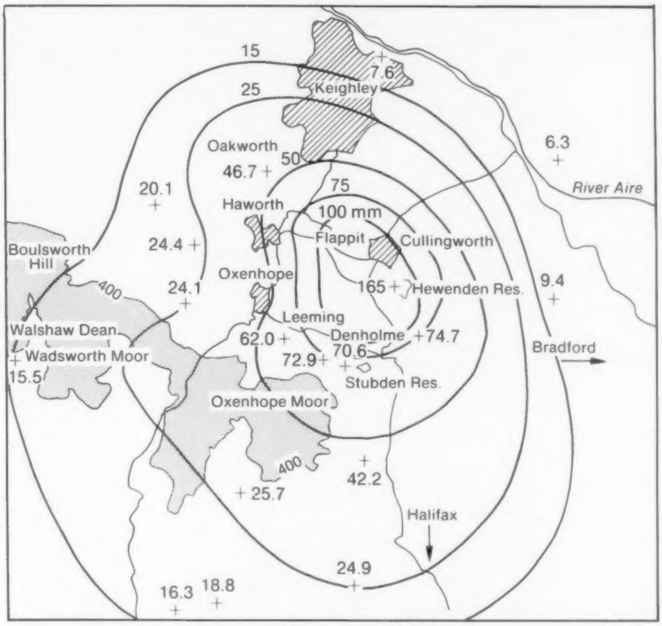

Figure 4. Twenty-four hour rainfall totals and isohyets on 11 June 1956 for the Hewenden Reservoir area.

Accounts of the damage are copious and graphic and leave no doubt about the severity of the rainfall and the accompanying flooding (Fig. 5). Fortunately there is good evidence to establish the location of the storm centre. According to Mr Lattin, the storm appeared to be worst on the hills above the Halifax–Keighley road, between Flappit and Denholme, which is some 2 km west of Hewenden Reservoir, where the maximum rainfall was observed (Fig. 4). This was presumably based on the fact that the worst flooding was in Cullingworth, through which Manywell's Beck flows, draining 2.05 km^2 of moorland in the area he identified. Just upstream of Cullingworth Gate the stream is conveyed under a mill yard in a culvert. This was so overloaded that the culvert burst, and the arch of a road bridge just downstream was also unable to accommodate the flow.

An estimation of the minimum rainfall that must have fallen in order to exceed the capacity of the bridge is found to be 115 mm (see Appendix). The actual value is likely to have been considerably larger than this, since the bridge capacity was conspicuously exceeded and since flood water was rushing down the three roads (from the west, south-west and east) that converge on Cullingworth Gate, resulting in extensive flooding and damage to properties and roads (Fig. 5). There are accounts of minor flooding in surrounding villages — Oakworth, Haworth, Oxenhope and Leeming, but only in the last was there evidence of something exceptional. Here residents 'saw the hillside break into streams' and tried to build barriers to prevent their homes from being flooded.

5. Rainfall

Evidence about the maximum observed rainfall is contained in British Rainfall 1956, and is supported by a letter from the Waterworks Engineer, City of Bradford to the Director, Meteorological Office dated 16 July 1956. (Times referred to are BST.) He wrote — 'The reservoir keeper at Hewenden informs me that the rain started at 6.45 p.m. The gauge was then empty after a fine day. The rain ceased by 8.30 p.m. and the gauge was read at 9.00 p.m. when 6.09 inches of rain was measured. A further 0.41 inches fell during the early hours of the 12th. At Stubden reservoir the keeper observed that the rain started at 6.45 p.m. and finished at 8 p.m. He then read the gauge, which was empty at 6.45 p.m. and found the rainfall to be 2.45 inches. A further 0.42 inches fell before 9 a.m. on the 12th'.

Daily (0900–0900 UTC) rainfall totals have been obtained from 19 gauges, including Hewenden and Stubden. There is also a storm total reading from an unofficial gauge in Oakworth of 1.6 inches (41 mm) from which the 24-hour fall at that site has been estimated to be 46.7 mm. All these data and the corresponding isohyets have been plotted in Fig. 4. There are places where clearly considerable doubt must exist, notably around the centre of the storm and also in the north-east quadrant. However, the overall pattern and the location of the 25 mm and 50 mm isohyets have been established with reasonable confidence. The isohyets have been drawn on the assumption that the centre of the storm was correctly located by Mr Lattin, and this therefore suggests a maximum rainfall in excess of that observed at Hewenden Reservoir.

Figure 5. Flood-water flowing down the Halifax Road, Cullingworth, on the evening of 11 June 1956, causing severe damage in houses and breaking down 36 metres of the wall along the road *The Yorkshire Observer*.

6. Storm efficiency

One method of classifying storms for the purpose of Probable Maximum Precipitation (PMP) studies (Wiesner 1970, WMO 1969) is to calculate the corresponding storm effiency (S_{eff}) which is defined as the ratio of maximum observed rainfall to the amount of precipitable water in the representative air column during the storm (NERC 1975).

The amount of precipitable water, W (mm) in a column of air of height z is defined as

$$W = \int_0^z \rho_w dz = -\int_{p_0}^{p_z} \frac{\rho_w}{\rho}\frac{dp}{g} = -\int_{p_0}^{p_z} \frac{s}{10^3 g}\, dp$$

where ρ and ρ_w are the densities of air and water vapour respectively in kg m^{-3}, s is the specific humidity or mixing ratio in g kg^{-1}, p the atmospheric pressure (mb $\times$ 10^{-2}) and g is the gravitation constant 9.81 m s^{-2}.

If no vertical soundings are available, it is assumed that the air mass in the storm is saturated and that the vertical humidity profile is represented by the screen level dew-point, following the saturated pseudo-adiabatic lapse rate. The precipitable water W can then either be calculated by using tephigrams to determine the mixing ratio s or by using tables which directly give the precipitable water as a function of height and dew-point (Wiesner 1970).

For the present study W was determined with help of the tephigram for an air column between 1000 and 200 mb, in 100 mb steps. Three storm efficiencies were then calculated for surface dew points of 12, 14 and 16 °C and an observed rainfall of 155 mm. The results are shown in Table III, which demonstrates clearly that the storm efficiency is very sensitive towards changes in the dew-point.

Attempts to reproduce the FSR calculations of S_{eff} have failed. Assuming a dew-point of 12 °C, a value of 5.93 is obtained as above, and 6.10 is found using Wiesner's (1970) tables, both substantially larger than the 5.3 quoted by FSR. To obtain an S_{eff} of 5.30 as above, the precipitable water content would have to be 29.2 mm, which corresponds to a dew-point of 13.5 °C.

Even with allowance for station and cloud-base altitudes as well as for a storm duration of 105 minutes rather than 120 minutes, a value of 5.3 could not be obtained. However, none of these possible allowances are mentioned in the FSR. Practical and theoretical problems inherent in defining effective precipitable water for this purpose deserve careful future examination.

In any case, examination of surface meteorological data for 11 June has revealed no evidence for a dew-point as low as 12 °C at Hewenden Reservoir during the storm (as assumed in the FSR); examination of Fig. 2 and Table II suggests instead a value of 16 °C. Although not explicitly mentioned in the FSR, it seems that the quoted low value was taken to be representative of the Hewenden storm on the grounds that it was the highest dew-point persisting for a 6-hour period. Though consistent with WMO advice for long-lasting storms (WMO 1969), this approach is suspect on two counts:

(a) Convective storms break out rapidly once critical conditions have been reached. Averaging over 6 hours may remove significant peaks, especially those related to the important diurnal cycle of surface heating.

(b) On this occasion it would seem that the 6-hour period chosen ran from the beginning of the storm (1800 UTC) to well after its end (0000 UTC, 12 June). Dew-points at the latter time are representative of the cool air deposited from the middle troposphere, rather than the warm air rising from surface layers which provides the high precipitable water content powering the storm, and should not be used to estimate storm efficiency.

Table III. Calculated storm efficiencies (S_{eff}) for dew-points of 12, 14 and 16 °C

Dew-point (°C)	Precipitable (mm)	S_{eff}
12	26.11	5.93
14	31.30	4.95
16	37.55	4.17

In the FSR, similar storm efficiency calculations were carried out for six other major 2-hour storms in England and Wales, giving values ranging from 3.04 to 3.86. On this basis it was concluded in that report that a probable maximum storm efficiency in the United Kingdom for a 2-hour storm is 3.86, whilst the value the present authors obtained for the Hewenden Reservoir (Table III) is 4.17. The difference is not great, and indeed is remarkably small given the uncertainties in the calculation, and doubts about the concept of storm efficiency.

Note that the probable maximum storm efficiency multiplied by the maximum observed precipitable water content gives the PMP which was originally derived to provide useful assessments of very intense precipitation for hydrological purposes, but seem now to be widely regarded as the Maximum Possible Precipitation (MPP). It is implicit in the FSR case against the Hewenden reservoir rainfall observation that it must be incorrect because it exceeds the local and national 2-hour PMP. Problems inherent in the concept of PMP are the subject of considerable controversy. The dangers of assuming identity between the practically useful PMP, and the probably indefinable MPP, will be addressed by the authors in another paper.

7. Conclusions

In the Flood Studies Report doubts were raised about a gauge rainfall observation of 155 mm in 105 minutes on 11 June 1956 on the basis that the corresponding storm efficiency was too high when compared with other storms (NERC 1975). In this study evidence is brought together that supports the original observation.

The authors estimated the dew-point, which is an essential variable for the calculation of the storm efficiency, to be considerably higher than that quoted in the Flood Studies Report, which then leads to an acceptable lower value for the storm efficiency. This suggests, that the original measurement of 155 mm was correct and that this event was indeed an outstanding storm in Great Britain with one of the highest observed rainfalls in 2 hours.

In any case, as the storm efficiency is very sensitive to changes in the dew-point, which generally has to be estimated for a particular site, it should not be used as the basis for the rejection of an actual rainfall measurement.

The controversy over the rainfall observation for this storm shows how important it is to investigate extreme events immediately and to summarize the facts in a report that is published and made available to the scientific community.

8. Acknowledgements

Two of the authors (J.F.R.M. and J.T.) wish to acknowledge the primary role and enthusiastic interest of our colleague V.K. Collinge to within a few weeks of his death. J.T. acknowledges support from an NERC studentship during the course of this work.

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Appendix

The discharge at Cullingworth Gate Bridge at the point of overtopping can be estimated with Manning's formula (Shaw 1984)

$$Q_P = \frac{AR^{2/3}S^{0.5}}{n}$$

With the area (A) of the bridge that had to be overtopped of 8.1 m^2, a hydraulic depth (R) of 1.62, a slope S of 0.015 and a roughness coefficient for unlined earth of 0.015 the discharge would be $Q_P = 91\ m^3\ s^{-1}$.

The precipitation generating the discharge between the rise and peak storm-flow is given by

$$P = 0.5(Q_P T_P) S A^{-1} R$$

where P is precipitation (mm), Q_P the peak discharge in $m^3\ s^{-1}$, T_P is time (seconds) to peak discharge, S is the shape function for the rate of hydrograph rise (0.8), A is the catchment area (2 050 000 m^2) and R is the index of the discharge coefficient (90% run off $\equiv$ 0.9).

Assuming: (i) a time to peak discharge (from start of hydrograph rise) of two hours (7200 s), and (ii) a discharge coefficient (R) of 0.9, the catchment mean precipitation would be 115 mm. This minimum value is already higher than the point value at the storm centre as calculated in the Flood Studies Report.

Review

Atmospheric data analysis, by R. Daley. 182 mm × 260 mm, pp. xiv+457, *illus.* Cambridge University Press, 1991. Price £55.00, $79.50. ISBN 0 521 38215 7.

In the past, when asked to recommend reading material on analysis methods, I have had to scratch around and suggest several articles in order to give a balanced approach. This book brings the material all together and fills a gap in the atmospheric science literature. The scope is wider than the title might suggest, including initialization and related dynamical theory as well as the spatial analysis aspects. It has an emphasis on the theoretical foundation, but includes practical applications. It is the second title in the Cambridge Atmospheric and Space Science Series.

Chapter 1 forms an introduction, including brief descriptions of the types of observations available and a short historical review of data assimilation from subjective analysis to the present via the start of computer predictions and analysis *circa* 1950. Most of the rest of the book requires a substantial mathematical background (advanced undergraduate level).

Chapters 2–5 cover early analysis methods including function fitting and successive corrections and then move on to statistical interpolation (sometimes called optimum interpolation or OI). The statistical interpolation equations are derived from the minimum variance (least-squares) principle, the alternative probabalistic viewpoint is not given. A continuous analogue of the equations is provided to illustrate properties of the algorithm, and some atmospheric physics, in the form of multivariate constraints, is introduced. A renewed interest in successive correction methods came from the realization that they could be formulated so as to converge to the statistical interpolation solution (appendix F).

Initialization is the process of adjusting the initial conditions so that they do not excite inertia–gravity waves in the early part of the forecast. Starting with geostrophic adjustment of the shallow-water equations the theory is developed, via quasi-geostrophic constraints and variational procedures, into normal mode initialization of the primitive equations (chapters 6–10). Dynamic initialization using damping time integration schemes and continuous data assimilation (motivated by the asynoptic nature of satellite observations) are dealt with in chapters 11 and 12.

Most operational forecast centres use an intermittent data assimilation cycle with a statistical interpolation analysis and non-linear normal mode initialization. To be different, the Meteorological Office uses a continuous (dynamic relaxation) data assimilation cycle with a modified successive correction method and no explicit initialization.

Statistical assimilation methods have the disadvantage of relying on average covariance functions to represent atmospheric structures/dynamics. Four-dimensional variational assimilation allows a two-way interaction between model dynamics and observations in the search for the optimum analysis. It is currently the subject of active research at several centres. The Kalman–Bucy filter evolves the forecast error covariance matrix (with dimension = number of grid-points squared!) using linearized dynamics. With recent forms of initialization (Laplace transform and bounded derivative) and notes on assimilation of hydrological, mesoscale and ocean data, these are introduced as 'Future directions' in chapter 13.

The chapters each have a set of questions at the end, some quite testing. A series of appendices give background material on several topics including normal modes and Bessel functions. There is an extensive bibliography.

Roger Daley covers the subjects comprehensibly and well, as one might expect from his contributions over the years. The book is well produced and up to date, however it is not light reading. I would have liked to have seen an abstract or summary for each chapter. The book is obviously useful as a textbook for advanced courses in meteorology and also as reference material for meteorologists and oceanographers involved in data analysis.

N.B. Ingleby

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